A Hybrid Converter with Series Capacitors Featuring Ultralow Added Installed Power

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Presented material is a result of the PhD project of Mr. Savvas Papadopoulos

Contents

- Introduction to Hybrid Concept
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- Analysis and Operation
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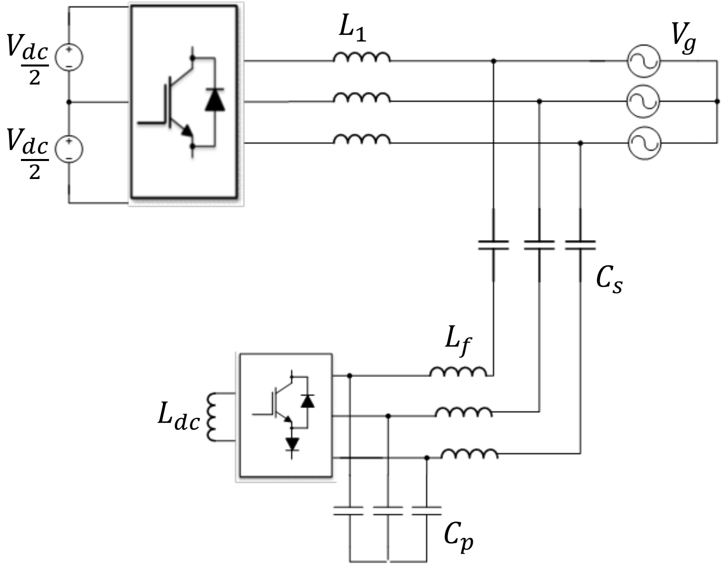
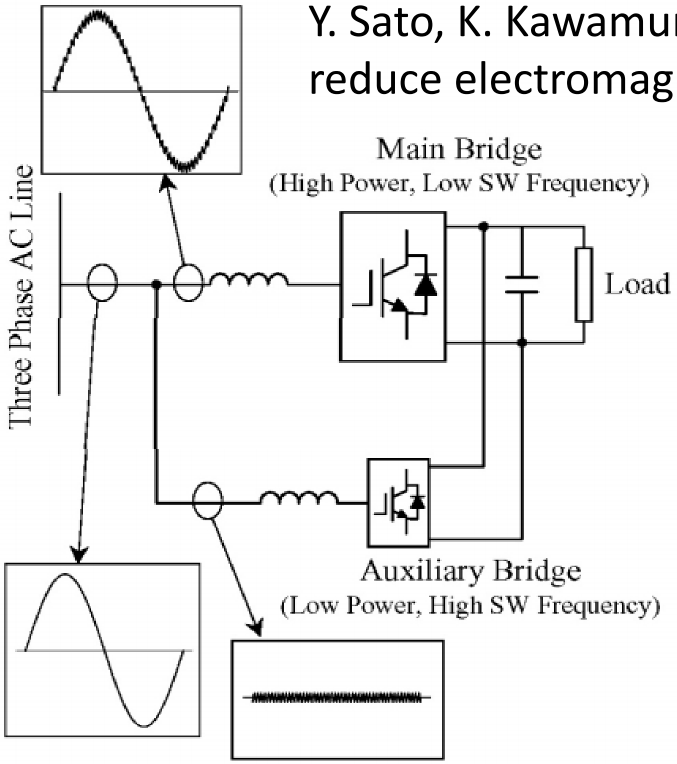


Background

- Inverters transform DC to AC
- Classified as Voltage or Current Source
- Medium voltage applications (typically ~3.3kVrms) require >5kVdc in DC link
- Characteristics of switching devices limit inverter capability to slow switching (<1kHz)
- Either use more complex multilevel topologies or install large filters (large passive components)
- Passive filters =variable attenuation =low @ 1st fsw cluster
- Alternative solutions employing active filtering have been proposed in the literature

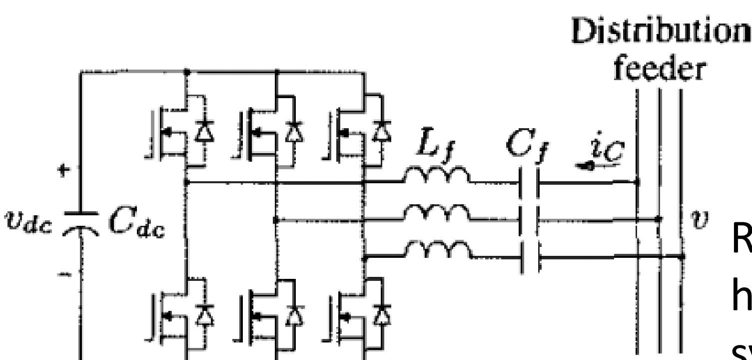
Related Work

Y. Sato, K. Kawamura, H. Morimoto, K. Nezu, "Hybrid PWM rectifiers to reduce electromagnetic interference," *IEEE IAS'02,* vol.3, pp. 2141-2146.



Main inverter = lower sw. frequency (max η)
Aux. inverter processes switching crt. ripple
⇒ **low I-rating** but SAME V-rating

Switching ripple > than typical 5th, 7th grid harmonics ⇒ much faster current controllers than in utility active filters



Series caps = used to block most of 50Hz voltage ⇒ Aux inverter= **Lower V-rating**

R. Inzunza, H. Akagi, "A 6.6-kV transformerless shunt hybrid active filter for installation on a power distribution system," IEEE PESC'04, Vol.6, pp. 4630-4636, *2004*

Related Work

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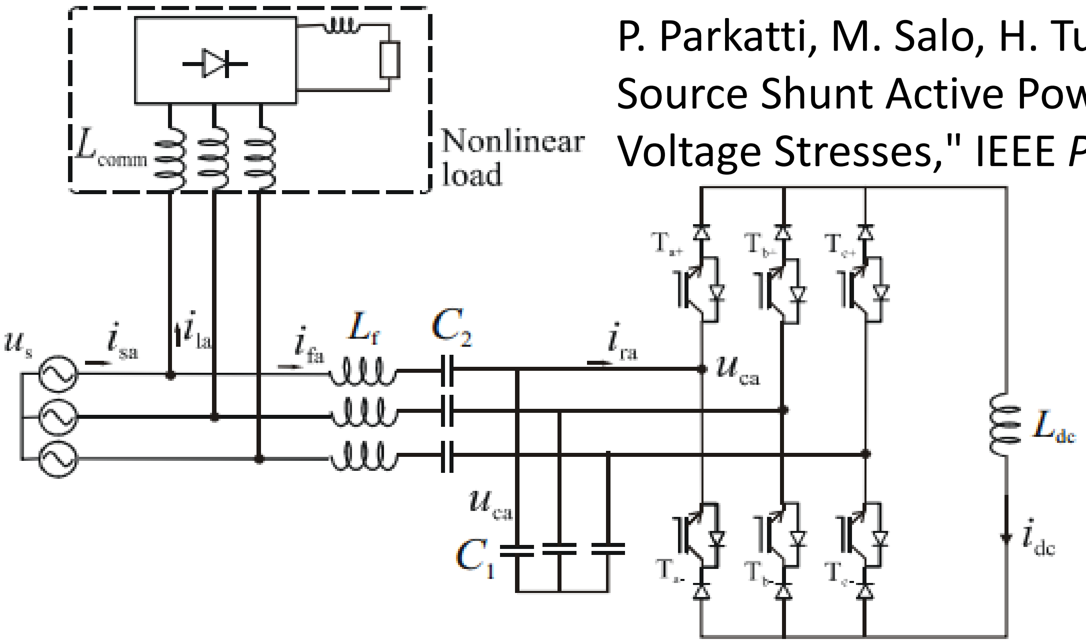


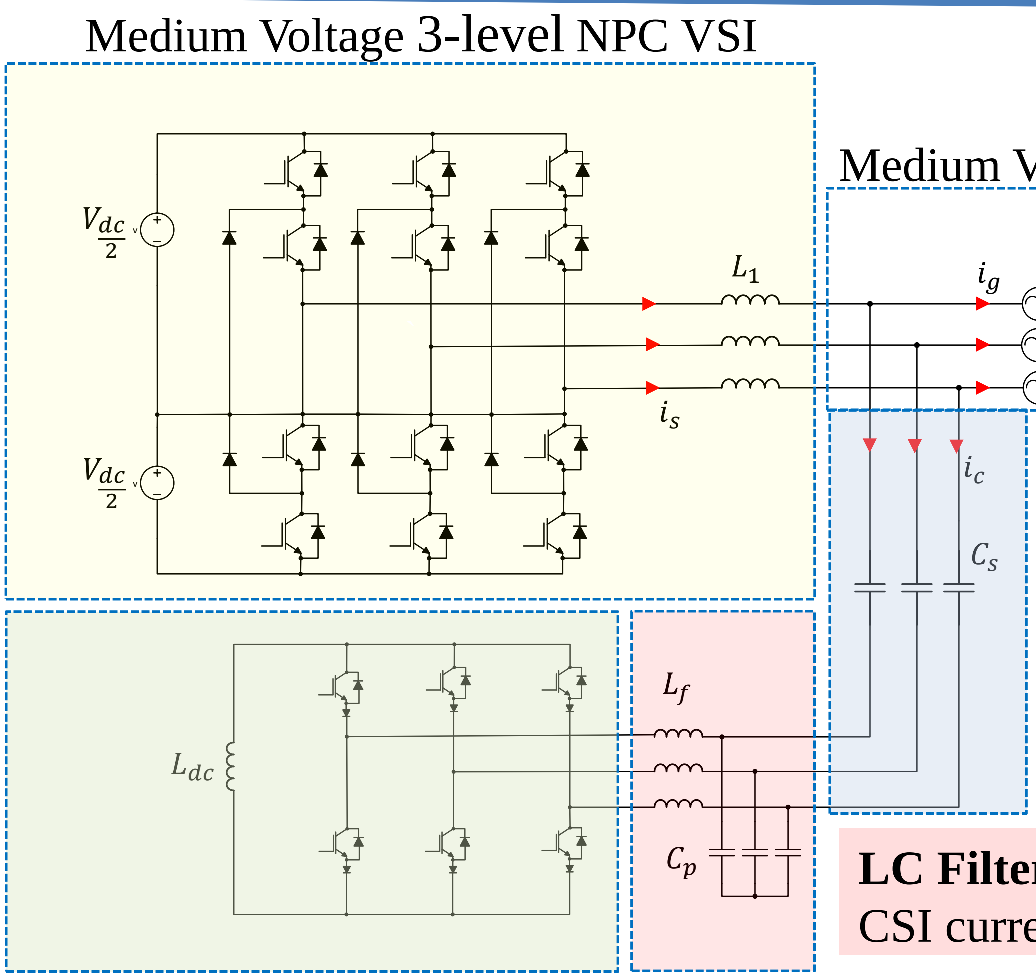
P. Parkatti, M. Salo, H. Tuusa, "A Novel Vector Controlled Current Source Shunt Active Power Filter with Reduced Component Voltage Stresses," IEEE *PESC'07,* pp. 1121-1125.

- Current controller – simpler
- Reduction of switch voltage rating to 50% of supply peak voltage has been reported
- Controlling DC voltage drift of series caps was necessary

Why using a CSI as Auxiliary Inverter in cancelling Main Inverter sw. ripple?

- Switching harmonics change very little with loading & is well defined
- No current controller needed $\Rightarrow$ lower fsw of auxiliary inverter
- Size of series caps =reduced /allows tighter design to fit whole operating range
- Suitable for retrofitting/upgrading PQ of existing MV inverters

Overview of Hybrid Circuit



Voltage ratings:
MV VSI =2x3kV dc-link
$V_{CSI\text{-}L\text{-}L}$ <1kVpk

Series Capacitors: Blocks most 50Hz grid voltage reducing V-ratings of auxiliary inverter but results in capacitive current absorbed from grid

LC Filter: removes the switching ripple from CSI currents but LC-prone to resonance

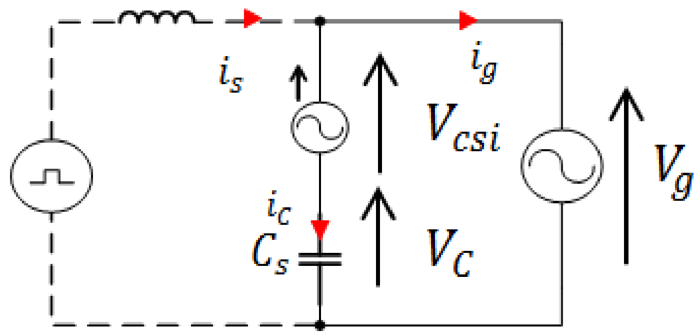
Low Voltage rated CSI: synthetises DIRECTLY (no current controller required) the distortion in main converter current

$\Rightarrow$ Could potentially operate with a much smaller switching frequency than an auxiliary VSI

20%V rating & 20% I rating
$\Rightarrow$ 4% Installed power

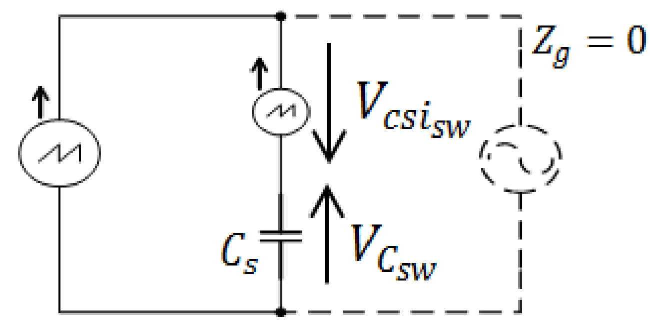
Circuit Design

Fundamental Frequency Equivalent Circuit



$V_g = V_{csi} + V_C$ $\quad$ $i_{csi} = i_C$

Switching Frequency Equivalent Circuit



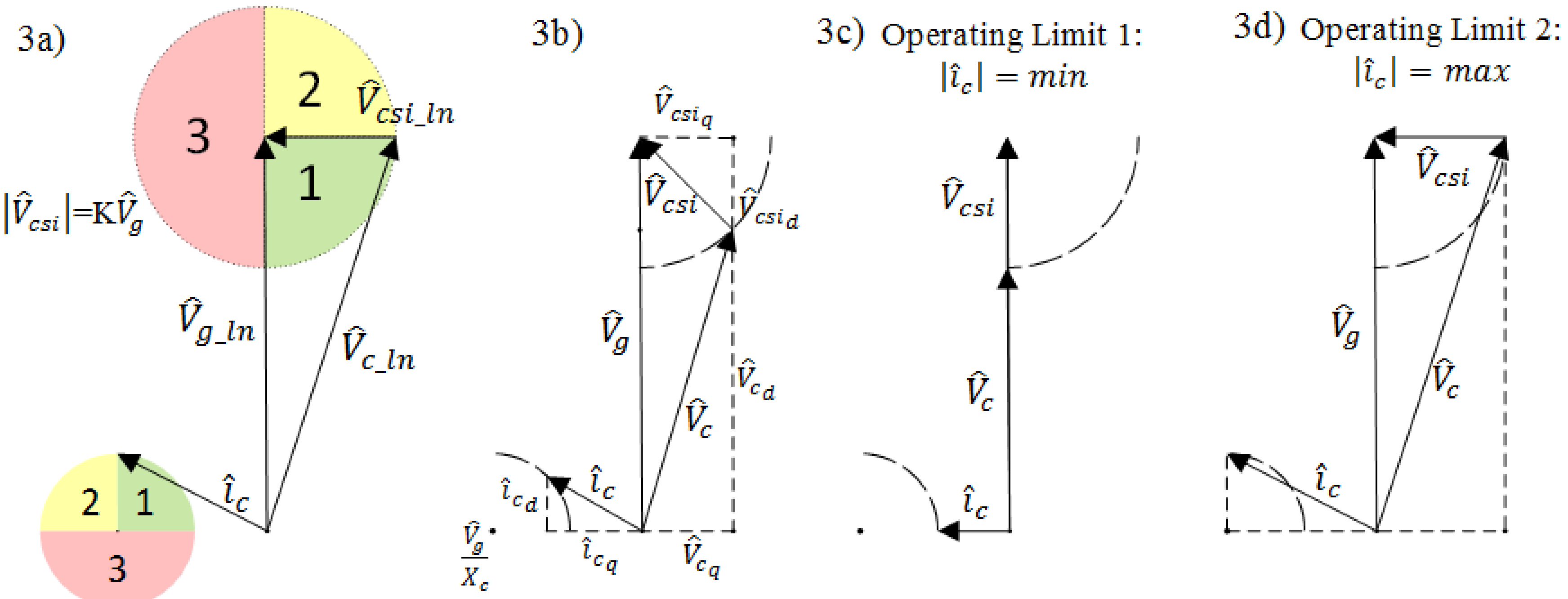
$V_{csi_{sw}} = -V_{C_{sw}}$ $\quad$ $i_{csi_{sw}} = i_{C_{sw}}$

- @ 50 Hz: the grid voltage is shared between the series capacitor and CSI depending on CSI current (controlled by P_{loss}&Q)

- @ $f_{sw\text{-}main}$: the voltage drop caused by switching current in series capacitor is reflected entirely across CSI inputs

- $\Rightarrow$ CSI V-stress = $\underbrace{\left|\vec{Vg}-\vec{Vc}\right|}_{\text{50Hz}} + \left|i_{sw}/(\omega_{sw}C)\right|$

Phasor Diagram (50Hz)



$$\hat{V}_{csi_q} = \hat{V}_{c_q} = 0;\ \hat{\imath}_{c_d} = 0$$

$$\hat{V}_{csi_d} = 0$$

$$|i_c| = i_{c_q} = \frac{(1-K)\hat{V}_g^{ln}}{X_c}$$

$$|i_c| = \frac{\sqrt{(K^2+1)}\hat{V}_g^{ln}}{X_c}$$

1: Reduced Current Region
2: Increased Current Region
3: Generating Region

- Series capacitor V-drop achieved by the CSI injecting a 50 Hz current
- A small active component may be required to cover losses (rectifier)
- Area “1” is the desired for operation

Design Procedure

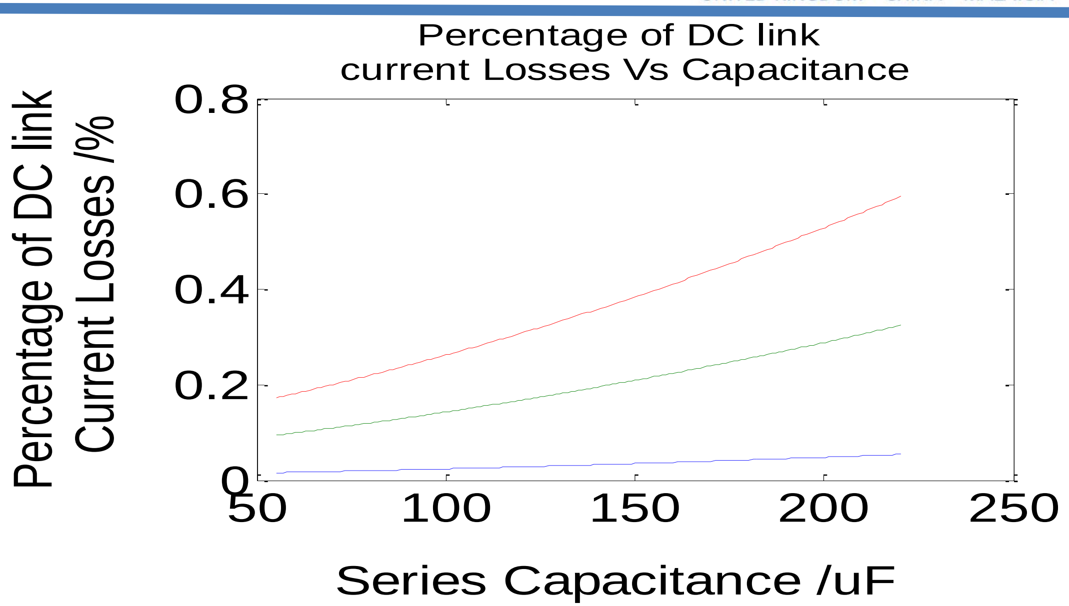
Smaller Cs reduces reactive current &conduction losses and overall CSI current rating
BUT
The switching ripple causes a higher voltage drop across Cs that needs to be mirrored by CSI

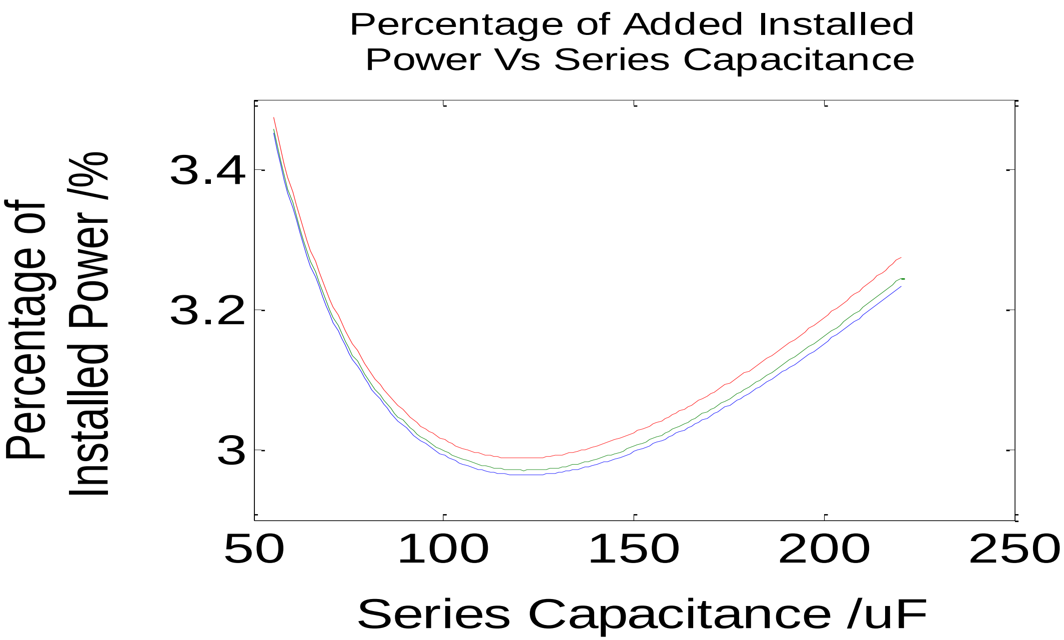
⇓

Varying Cs can have adverse effects on CSI installed power

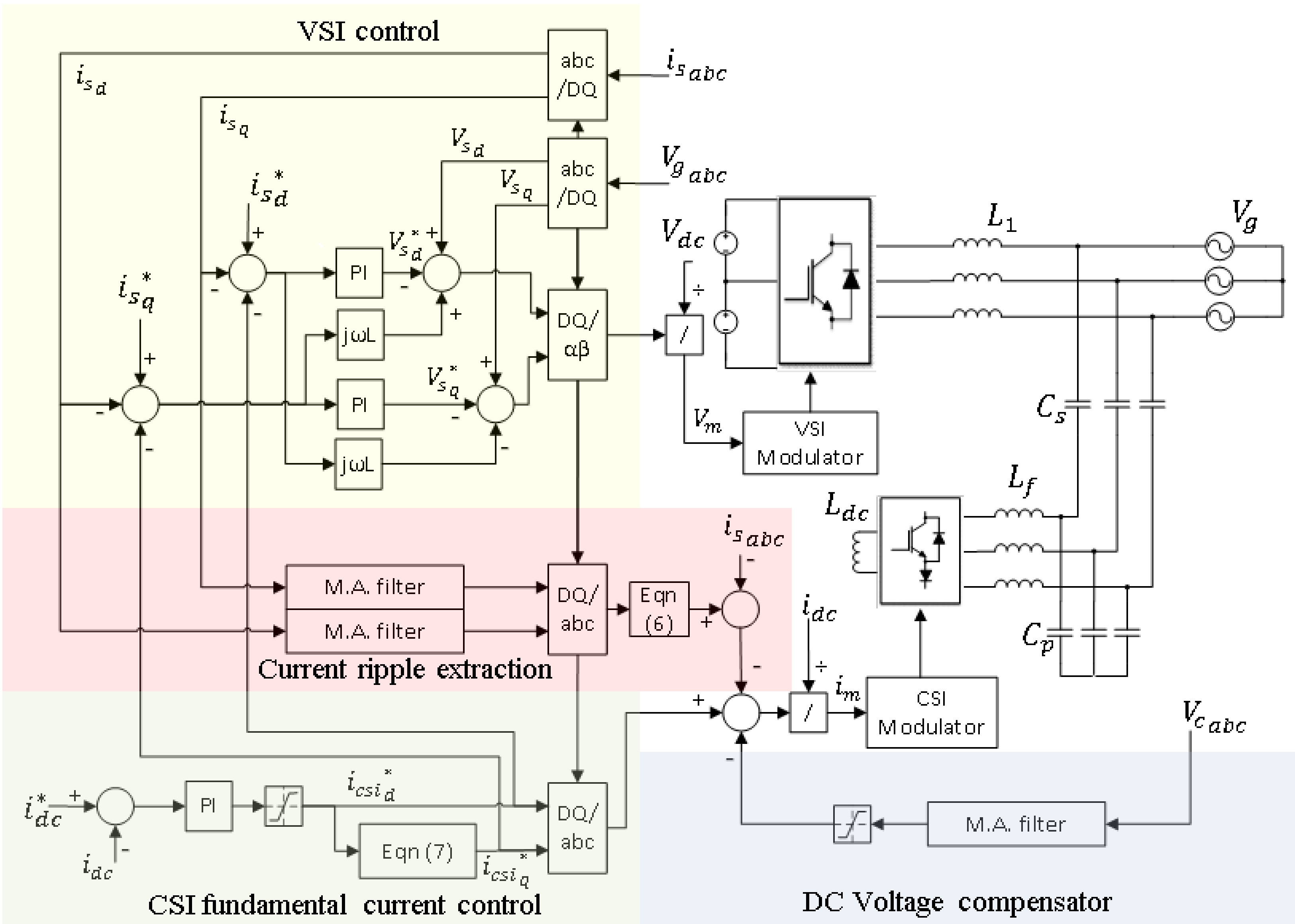
⇓

Determining an optimum design where P installed is minimised is possible





Control System



Simulation Results

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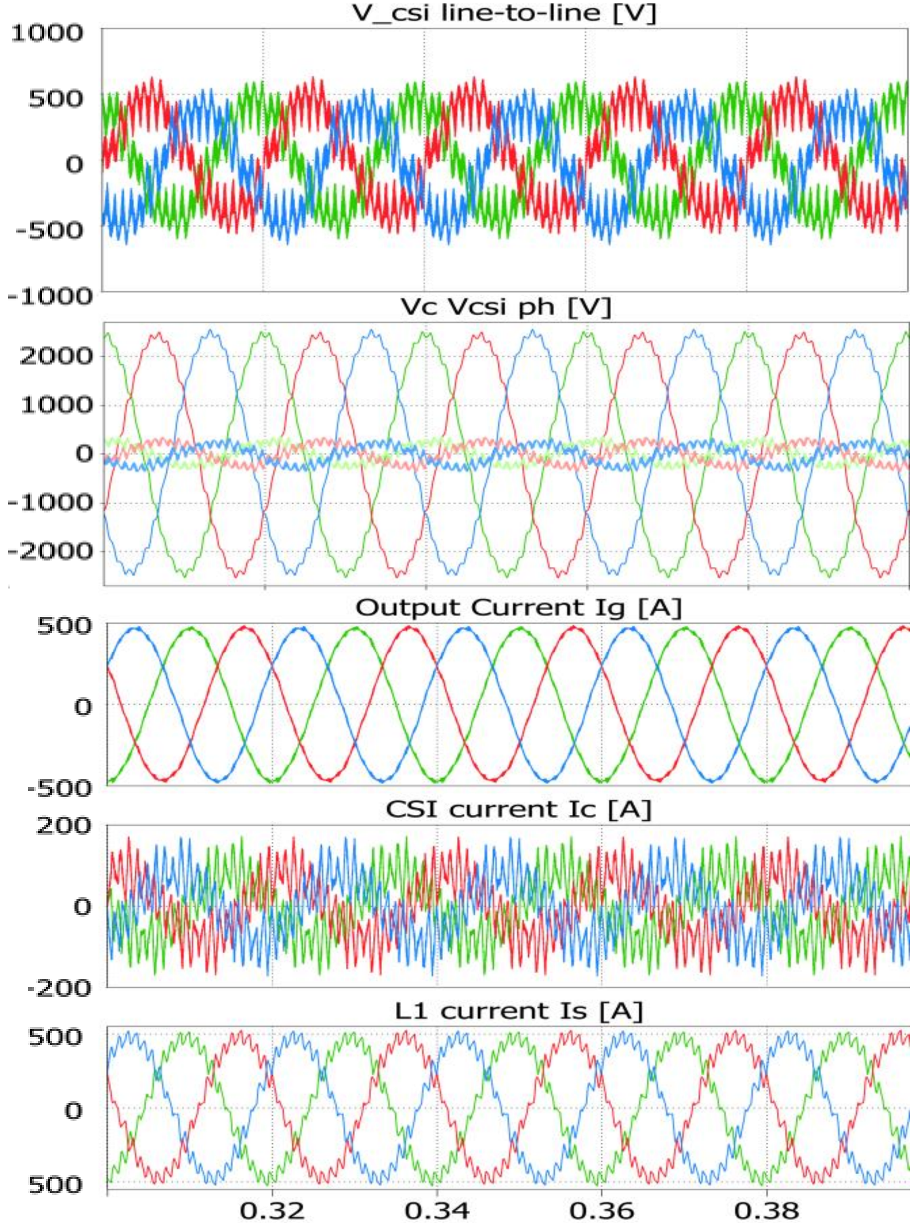
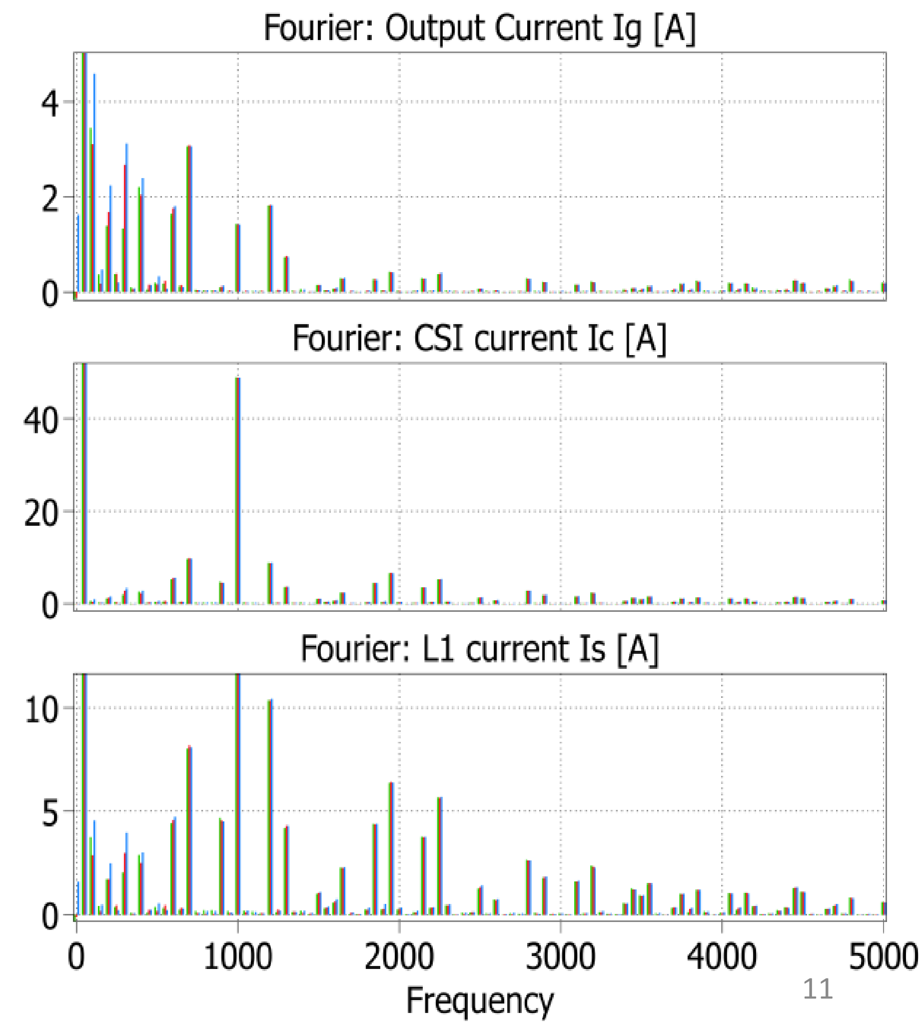
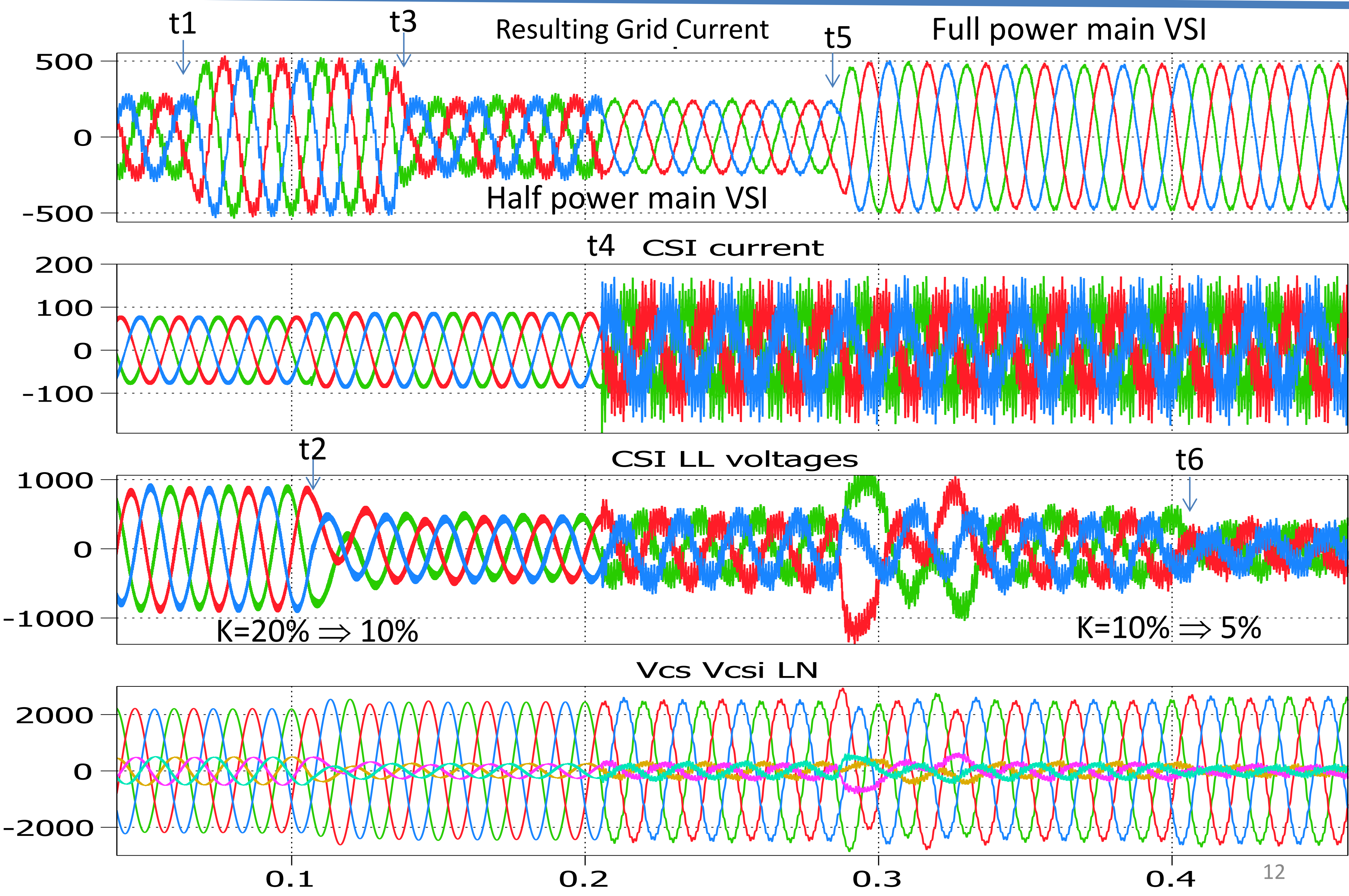


Main 3L inverter: V_g=3.3kV; I_g=330A_{rms}; V_{dc}=5kV
S=1.89MVA; f_{sw}=1kHz; C_s=110μF
CSI: L_{dc}=20mH; I_{dc}=184A; f_{sw}=30kHz; C_f=11μF



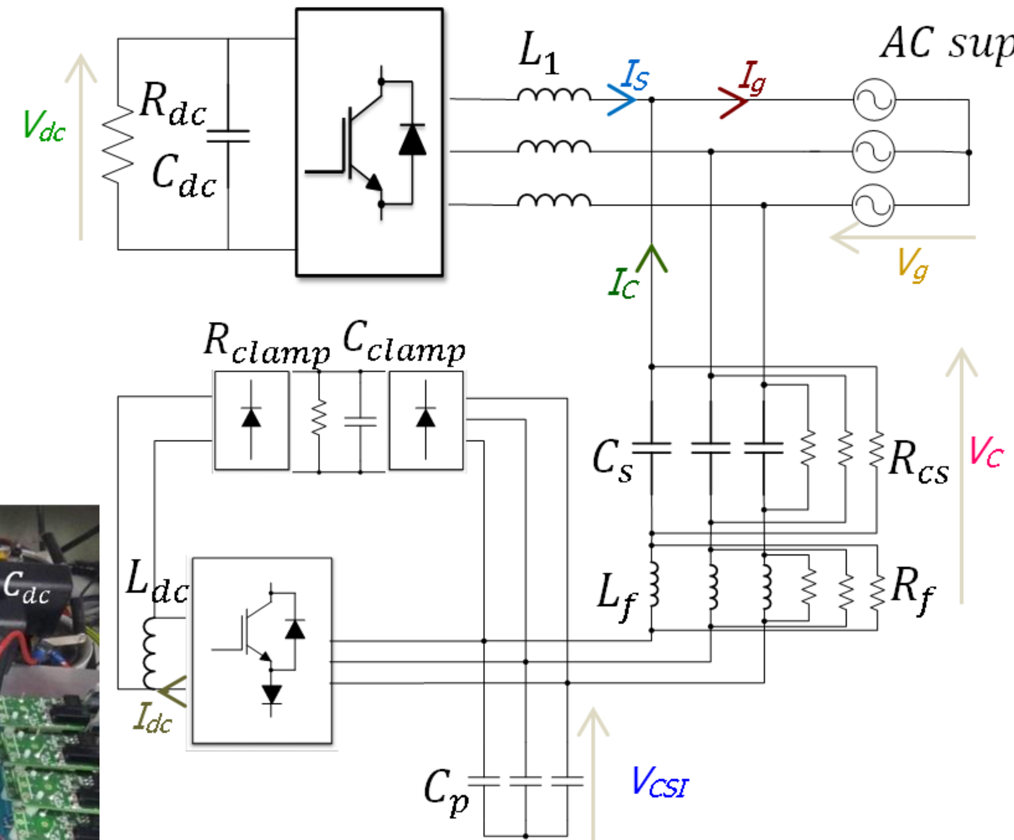
Transient Performance

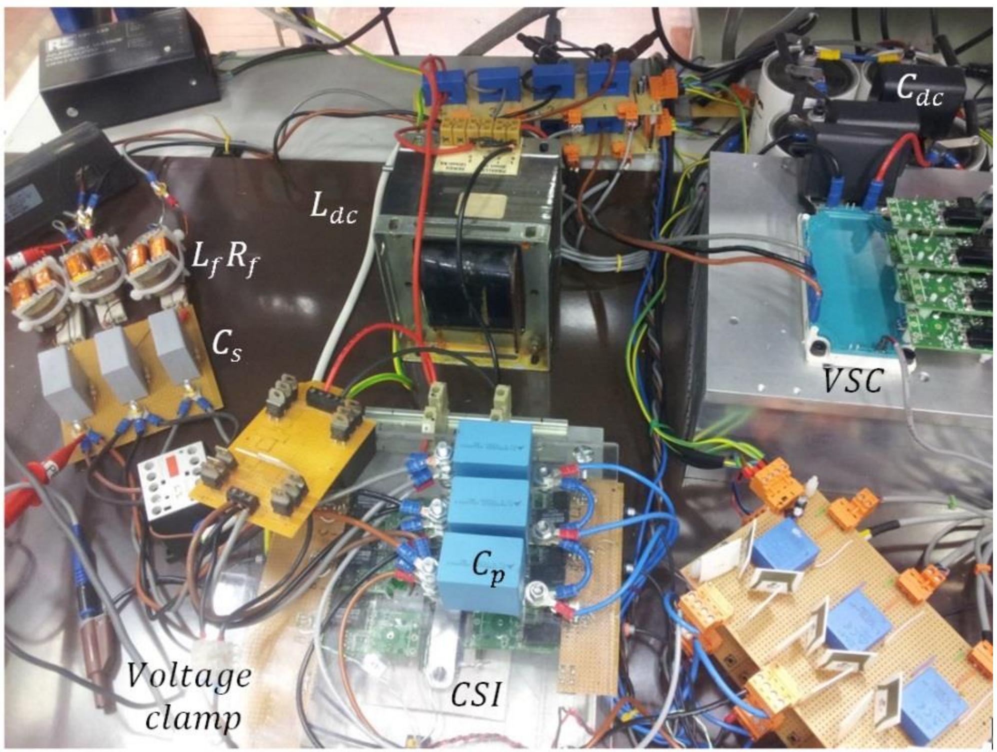


Experimental Evaluation

VSI working in Rectifier mode

- V_g = 415Vrms line
- $V_{dc\text{-}vsi}$ = 750V
- $P_{dc\text{-}vsi}$ = 4.2kW
- $f_{sw\text{-}vsi}$ = 1kHz
- $f_{sw\text{-}csi}$ = 40kHz
- $I_{dc\text{-}csi}$ = 5A





Parameters of the circuit:

$L_{1(vsi)}$ = 11mH; C_s = 12µF;

C_p = 1µF; $L_{f\text{-}csi}$=0.3mH; R_f=50Ω;

$L_{dc\text{-}csi}$ = 30mH C_{clamp}=20µF

Experimental Evaluation

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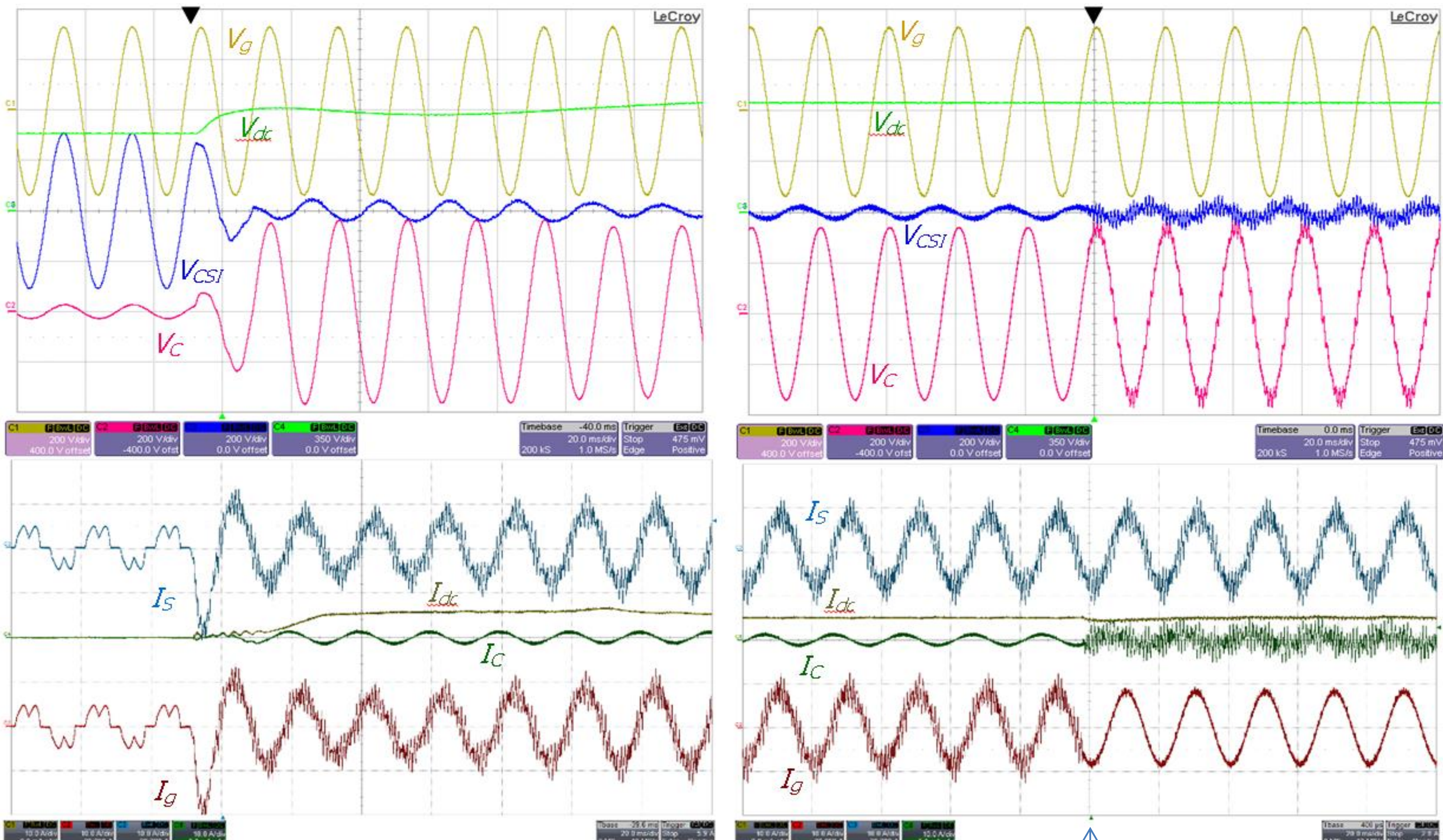
Transient tests



Main VSI current

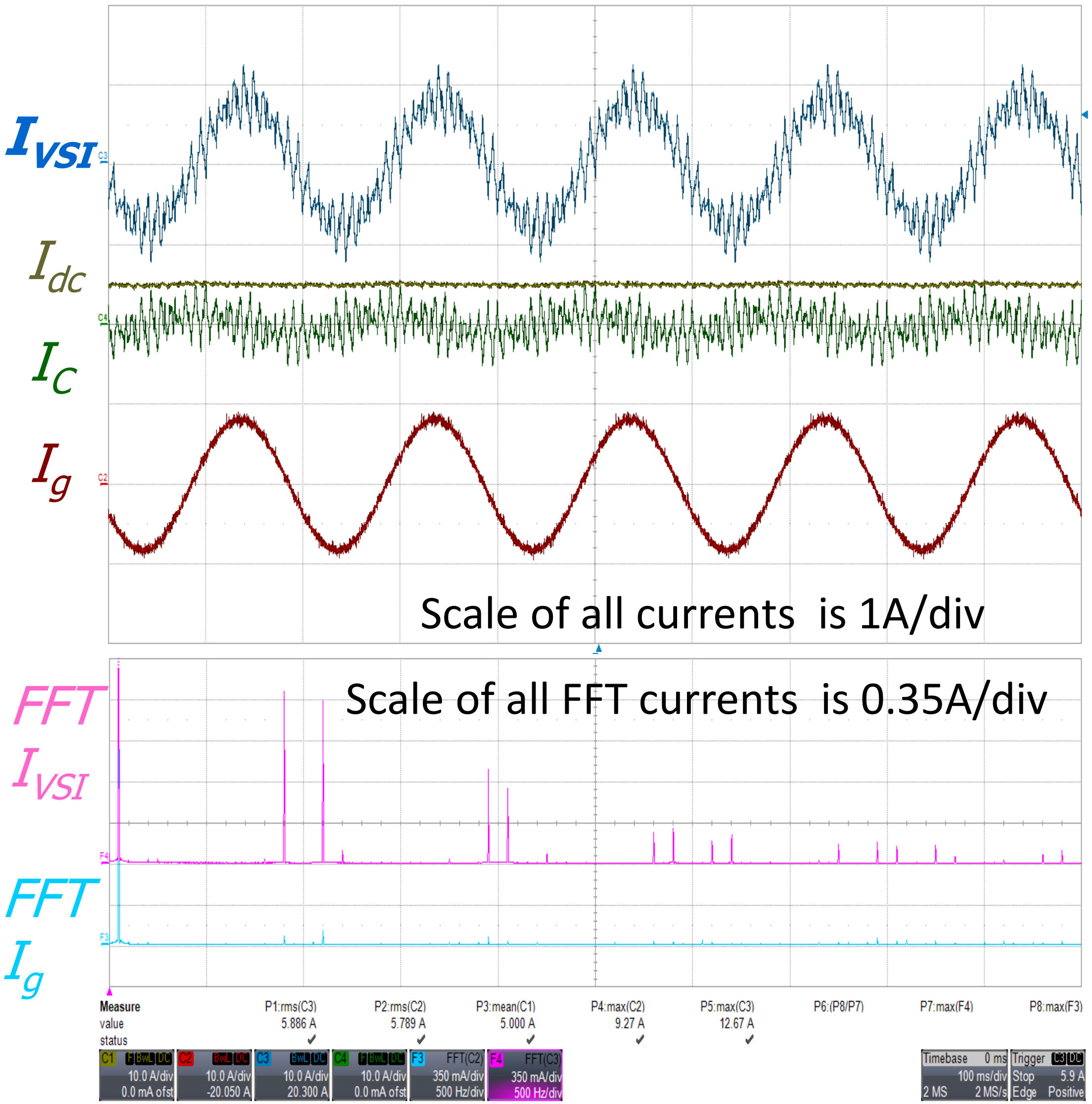
Grid current

CSI voltage (top blue) drops significantly after CSI activation

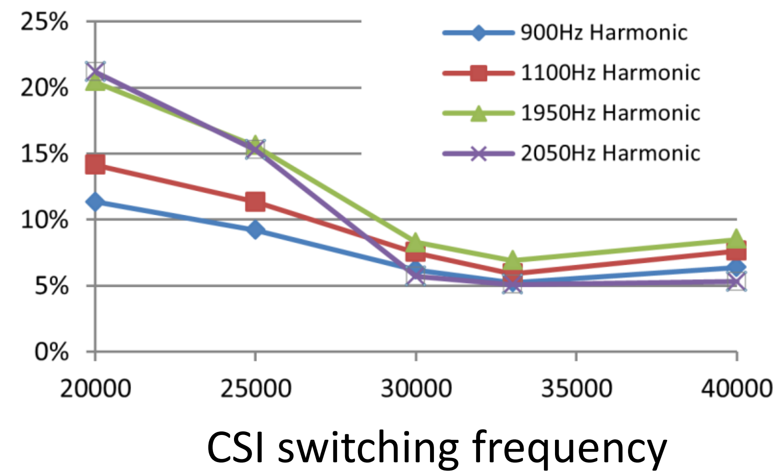
Start Active Ripple Cancelation

Experimental Evaluation

Assessment of current ripple cancelation



Remaining sw. harmonics as percentage of original VSI switching harmonics



A reduction of 20 times of the switching ripple has been demonstrated

Attenuation is independent of harmonic order

Conclusions

- Switching ripple filters are subject to full current stress/ratings
- Traditional shunt active filters are rated at full grid voltage
- Active filters with series connected caps have been proposed for harmonic compensation (5,7,11 etc) but voltage reduction is highly dependent on harmonic profile $V_{c\text{-}h} = I_{c\text{-}h} / (\omega_h \cdot C)$
- Switching ripple profile changes very little with operating conditions
- Hybrid Active Filter with ultra-low installed power is proposed and validated using simulation (MW) and experimentally (kW)
- CSI rated at 20 % of voltage and 20-30% of current of main inverter
- Only 4-6% added installed power of main inverter
- The hybrid solution is suitable for retrofitting old VSI/meet new PQ
- Enables design of main inverter with much smaller inductor/very large current ripple